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Cryogenic Delay Line for Far-IR Interferometry in Space

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1 Introduction

Direct-detection interferometry in space at far-IR/submillimeter wavelengths holds the promise of opening up an entirely new domain of astrophysical research. High angular resolution observations at wavelengths of 40-400 microns will allow us to determine the star formation rate as a function of redshift, and investigate fundamental questions relating to the history of star formation and the evolution of the universe (Swain 1998; Mather et al. 1998; Rieke et al. 1999). High angular resolution is required to avoid confusion due to the extragalactic background, with the highest resolution only being accessible through the use of long-baseline interferometry. At these wavelengths cryogenic optical systems are required, augmented with the active servo systems necessary for interferometry. One of the most challenging and crucial components of an interferometer is its delay line. We have designed and assembled a prototype cryogenic delay line to provide delays of up to 0.5 m that we are now in the process of testing. Its design, current status, and ongoing development are described.

2 Design Requirements for Far-IR Interferometry

Although two missions studies for far-IR space interferometry, SPIRIT and SPECS, are presently being developed at NASA's Jet Propulsion Laboratory and Goddard Space Flight Center (Shao et al. 2000; Leisawitz et al. 2000), no direct detection long-baseline interferometer has ever previously been designed, let alone built, to work at wavelengths longer than about 20 microns. The far-infrared and submillimeter require low temperature optics and extensive baffling for background limited observations. Although the optical delay line designed for the Space Interferometry Mission (SIM) will be able to survive thermal-vacuum testing, it is unsuited for cryogenic operation because of the large number of axles and moving parts it contains. In fact the SIM breadboard design has only been tested to survive -20 to 60 C in a hard vacuum, and is only intended to operate at 10 to 30 C. An active adjustable delay line, with a stroke of more than a few cms, has yet to be demonstrated for operation in a cryogenic environment. Interferometers must typically compensate for many meters of delay path, although with a maneuverable space interferometer this may be reduced to several tens of centimeters. The most challenging requirement of the design is therefore the need to provide a stroke of the order of 0.5 m, without using rotating axles which would potentially seize.

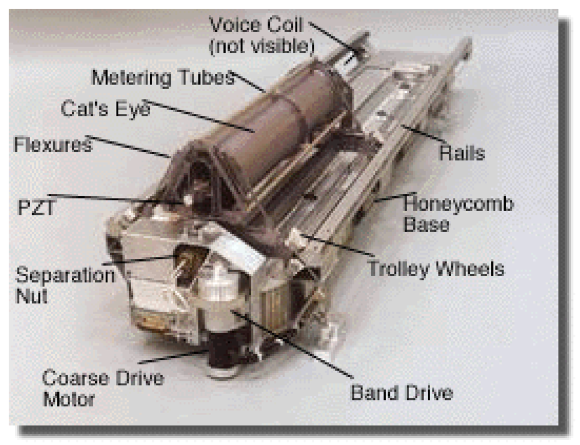

Figure 1: The large number of axle bearings in the SIM delay line make it unsuitable for cryogenic operation.

The motion of the delay line should not degrade the measured fringe visibility; thus path-length vibrations, angular fluctuations, and the lateral shear of the optical beams must be minimized. The sensitivity to each of these effects depends on the chosen design. We have adopted a movable cat's eye optical design, typical of ground-based interferometers, and have required the total visibility losses to be less than 1%. The cat's eye is similar to a retro-reflector in that the input and output beams are always parallel, but lateral motions of the cat's eye double the shear between the input and output beams. To maintain visibility losses due to shear to be less than 0.5% for a 10 cm beam implies a straightness of travel of 250 μm over the full stroke. The requirement for 0.5% loss due to piston jitter is 1.2 μm at a wavelength of 100 μm.

Designing and building a cryogenic delay line with a high degree of reliability is a major technological challenge. We are exploring two designs that are substantially different from the delay line being used with SIM. Our objective is to design a system without the use of axles, providing 50 cm of delay (25 cm travel), that is free from sliding friction and that can be operated in the hard vacuum of space to temperatures as low as 4 K.

3 Double Porch-Swing Delay Line

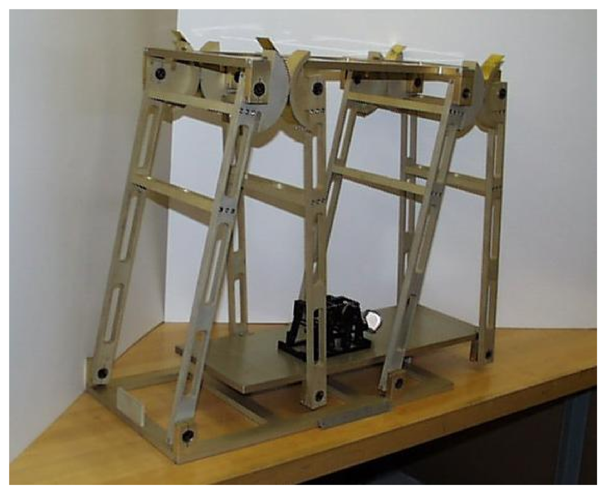

Figure 2: Double-porch-swing carriage using flexure pivots.

The earliest design that we considered uses flexure-pivots to provide linear travel with a "double porch-swing" coupling. This concept was developed by Don Jennings at NASA GSFC for SIRIS, a balloon-born LN2-cooled FTS system operating with a 12.5 cm linear travel. The same concept is being considered for use in the SPIRE spectrometer on FIRST. Our prototype, shown in Fig. 2, has been manufactured at NASA Goddard and delivered to JPL. It provides the required 25 cm travel and accommodates our optics. At JPL we will test the rigidity and vibration characteristics as well as the expected aging of the flexure pivots.

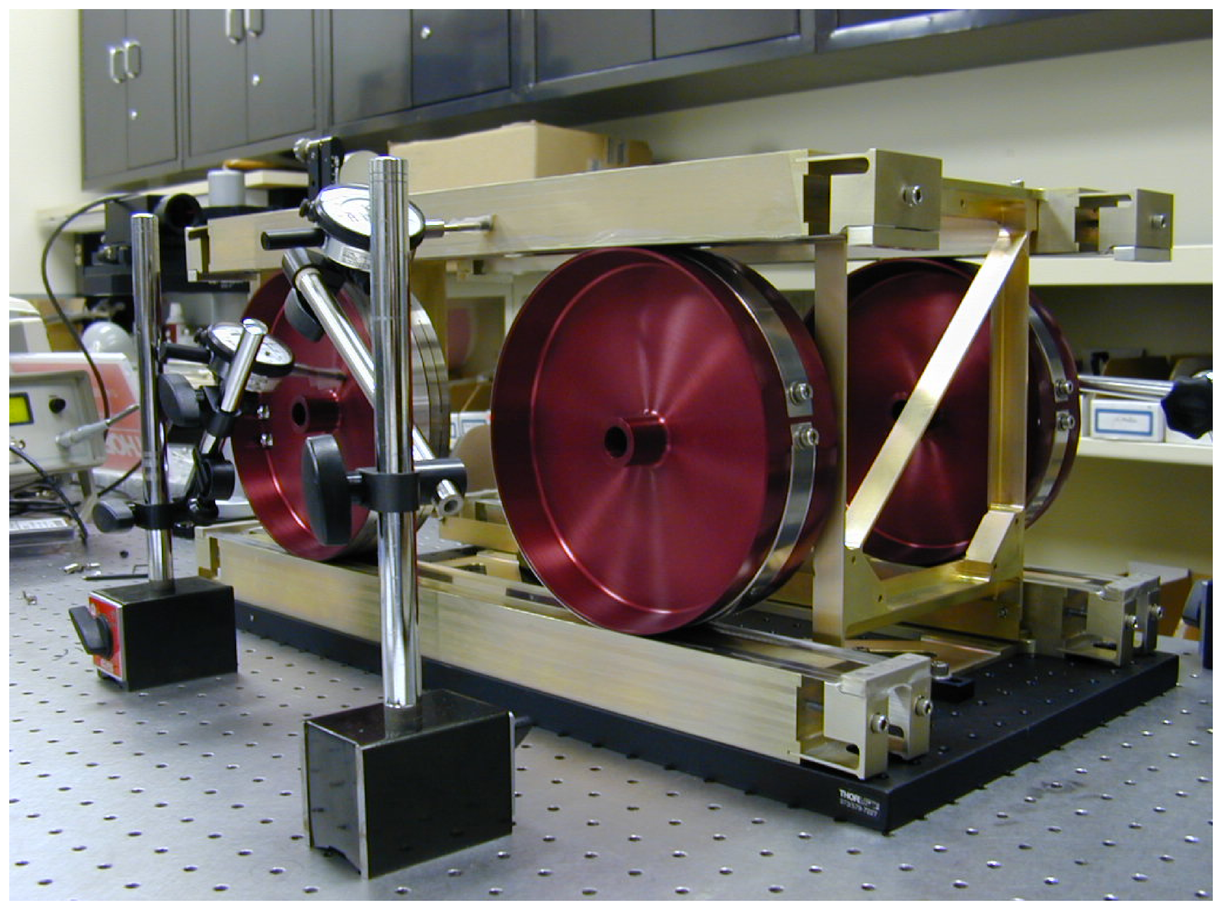

Figure 3: Cryogenic delay line with wheels constrained by straps. The upper platform supports the optics and rolls along the top of the wheels.

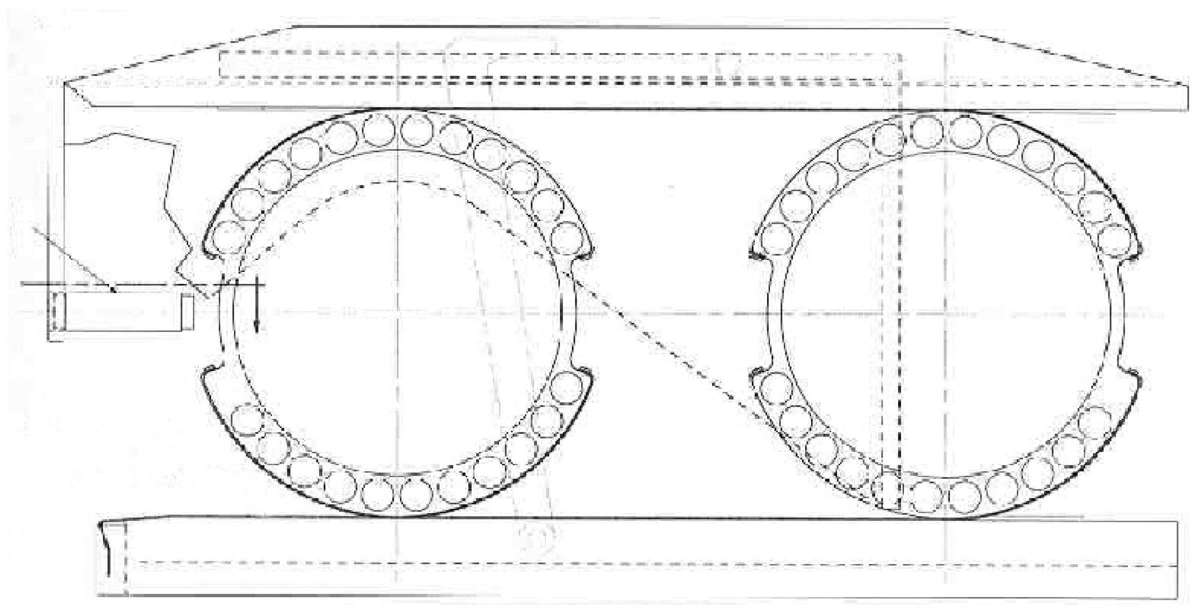

Figure 4: Early conceptual drawing of strapped-wheel delay line design.

4 Strapped-Wheel Delay Line

Because of concerns about the complexity and rigidity of the double porch-swing design, we have developed an entirely new design as shown in the photograph of Fig. 3 and the conceptual drawing of Fig. 4. The principle of operation is simple: an upper platform rides on top of the wheels, and from the platform are suspended the optics of the delay line. By rolling the platform across the wheels the optics can be moved back and forth in a straight line, as illustrated in Fig. 5. There are no axles in this system; the wheels are constrained only by straps.

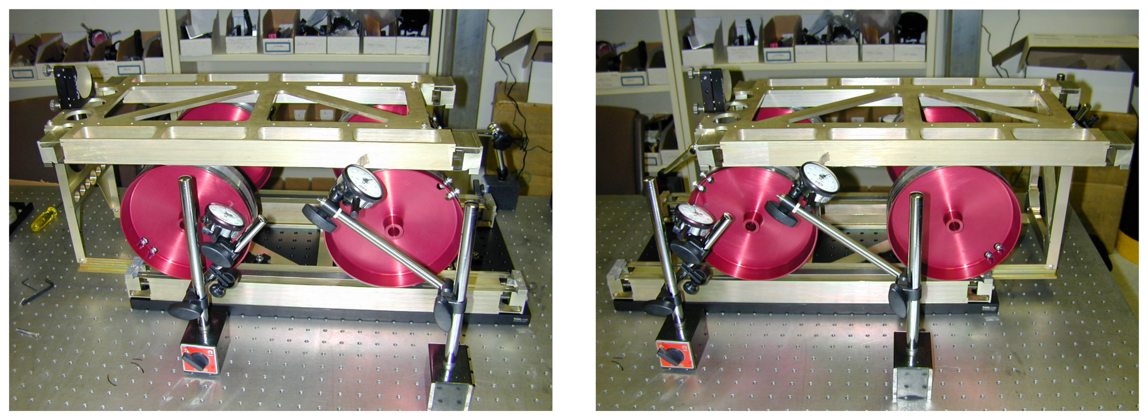

Figure 5: Left and right motions of carriage.

In our design each wheel has three straps, visible in Fig. 6. Two outer straps are held with an adjustable preload at the end of the bottom stage, pass underneath the wheel, on the left and right rim, and terminate on the end of the upper stage above where they were launched. For each pair of wheels on the left and right-hand side of the carriage there is also a strap that binds the pair together as a unit, passing around the outside circumference of the pair and so setting the wheel separation. The alignment of the wheels is tuned by adjusting the preload tension in the outer strap launchers. The carriage is manufactured entirely from aluminum with the exception of the the stainless-steel straps and the magnetic carriage preload. The carriage preload comprises 24 Neodymium Iron Boron magnets (0.5-inch in diameter), carried in counterbores within the aluminum base, which clamp (across an air gap) to a pair of steel rails suspended from the upper platform. This provides remarkable rigidity. The carriage has been tuned for a run out of 25 μm over its full travel—a factor of 10 better than our requirement.

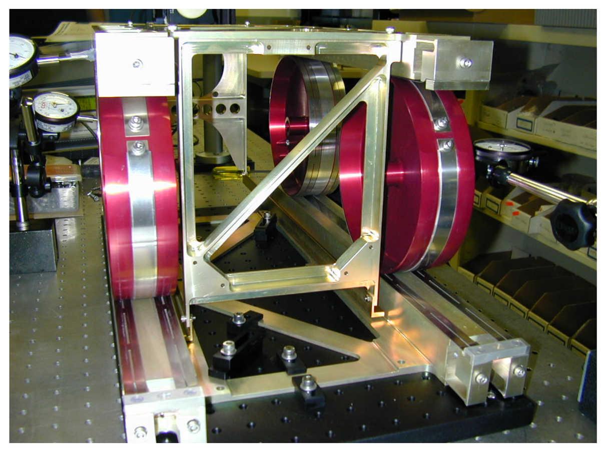

Figure 6: View showing wheel straps.

5 Cat's Eye Optical Design

Long delay lines used for ground-based stellar interferometry typically use a cat's eye design similar to the one depicted in Fig. 7. Collimated input beams arrive parallel but to one side of the optical axis of a parabolic mirror, are focused to a flat mirror, and are then re-collimated and output on the opposite side of the axis, parallel to the input beam. This design allows rapid pathlength corrections to be introduced by a small piezo-driven flat mirror at the focus of the parabola.

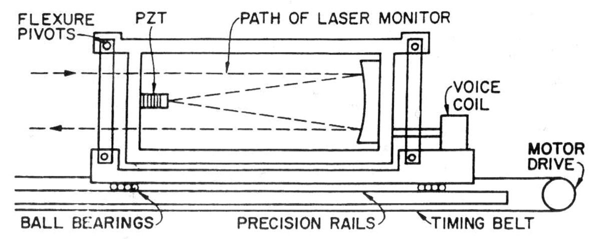

Figure 7: Typical delay line design for ground-based optical interferometers (Shao et al. 1988)

Our design is sized to accommodate 10 cm diameter beams at a wavelength of 100 μm, yielding a Fresnel number of 10 at a distance of 2.5 m. The parabolic mirror is 123 $\times$ 254 mm with a 381 mm focal length, manufactured by Axsys Technologies as a lightweighted diamond-turned 6061-T6 aluminum mirror with a surface expected to be 0.25–0.50 waves peak-to-peak (HeNe) over the 10 cm subapertures. This will provide a $\lambda/30$ surface at a wavelength of 10 μm, where preliminary tests will be conducted.

6 Metrology and Control System

The metrology and servo control system for the delay line is being implemented using Pentium III PCs running RTLinux, and is modeled after the control system of the CHARA Array (ten Brummelaar 2000). A pathlength-control servo loop with a sample rate of 2 kHz will be adequate to control the jitter and easily obtainable using PC-based hardware and hard real time software. The delay will be monitored with a Zygo ZMI-2000 metrology system with a compact single-beam interferometer and PC measurement board, providing a resolution of 0.6 nm, position range of ± 21.2 m, a maximum velocity of 4.2 m/s, and a readout rate of 60 kHz.

A two-stage servo will be implemented comprising the piezo transducer (PZT) on the cat's eye assembly, and a cryogenic stepper motor. The stepper motor (Phytron VSS 42 model) is, is configured to provide 0.47 μm/step in microstep mode and 9.4 μm/step in full-step mode, allowing the full range of travel to be scanned in 26 seconds. The piezo actuator is a custom Physics Instrumente HVPZ-239 model, with sub-nm resolution and mounted to provide a full-wavelength stroke at λ=100 μm. To compensate for the loss of travel at cryogenic temperatures, the PZT is mounted in a momentum-compensated mechanical flexure linkage which holds the cat's eye secondary.

7 Current Status and Future Plans

The strapped-wheel delay line prototype is largely complete, and initial mechanical tests have shown it able to meet or exceed our requirements. The optics and PZT have been installed; the fully assembled system is undergoing warm duration tests. Work is underway to integrate the metrology within the control system. We are also in the process of a warm mechanical evaluation of the double porch-swing design. We anticipate cryogenic tests of the strapped-wheel delay line in the near future.

As part of our long-term goal of developing a fully operational testbed for far-IR space interferometry, we intend to design and build a background-limited far-IR beam combiner. As illustrated in Fig. 8, microwave components can be laser micromachined for use at 2 THz (λ=150 μm), and in principle structures for wavelengths as short at 60 μm may be made (Walker et al. 1998). In collaboration with Chris Walker and his group we are designing and testing the basic waveguide components for λ=100 μm, including magic tees and directional couplers, and are planning to design and build a three and four-input beam combiner for direct detection synthesis imaging, similar to the single-mode fiber and integrated optics combiners of FLUOR (Coudé du Foresto et al. 1998) and IONIC (Malbet et al. 1999).

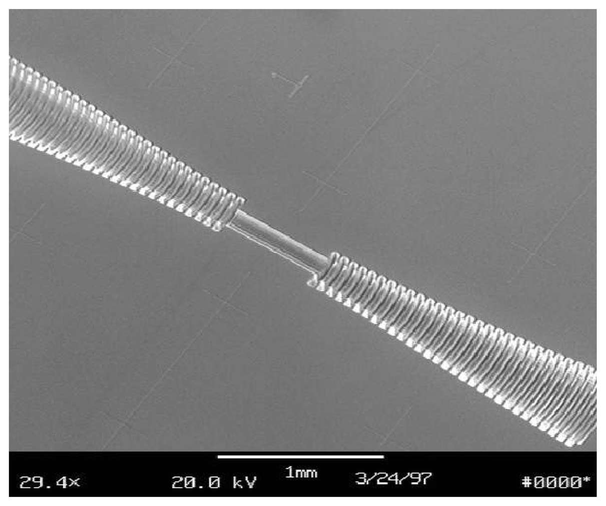

Figure 8: Laser machined waveguide structures, will be used to build a single-mode direct-detection beam combiner for λ=100 μm. (Courtesy of Chris Walker, Steward Observatory)

References:
T.A. ten Brummelaar 2000, Proc. SPIE 4006, 564; V. Coudé du Foresto et al. 1998, Proc. SPIE 3350, 856; D.T. Leisawitz et al. 2000, Proc. SPIE 4013, 36; F. Malbet et al. 1999, Astron. Astrophys. 138, 135; J.C. Mather et al. 1998, http://www.gsfc.nasa.gov/astro/specs/specs_3_7.pdf; G.H. Rieke et al. 1999, http://mips.as.arizona.edu/MIPS/fircase3.pdf; M. Shao et al. 1988, Astron. Astrophys. 193, 357; M. Shao et al. 2000, Proc. SPIE 4006, 772; M.R. Swain 1998, Pub. Astron. Soc. Pac. 110, 991; C.K. Walker et al. 1998, Proc. SPIE 3357, 45.

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